Wideband and Dynamic Characterization of the 60 GHz Indoor Radio Propagation – Future Home WLAN Architectures

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Abstract

This paper presents some results of a study concerning the radio propagation at 60 GHz in residential environments performed by the IETR (Electronic and Telecommunication Institute of Rennes, France). This study is part of a RNRT[1] project named "COMMINDOR"[2]. This exploratory project concerns the very high data rate (155 Mbps) and small range (about 10 m) radio communication systems for future home networks, which will permit multimedia equipment interconnection and control.

The study is based on several measurement campaigns realized with a channel sounder based on the sliding correlation technique. This channel sounder has a 500 MHz bandwidth and a 2.3 ns effective time resolution. The measurements have been performed in residential furnished environments. The study of the angles-of-arrival (AOA) emphases the importance of openings (such as doors, staircase, etc.) for the radio propagation between adjacent rooms. A particular attention is paid to the influence of human activity on radio propagation. It is shown that people movements can make the propagation channel unavailable during about one second. From the characterization study of the indoor radio propagation, several recommendations concerning the deployment of the very high data rate 60 GHz wireless networks are derived.

Key words: Indoor radio propagation, Millimeter-waves, Channel sounding, 60 GHz, Space-time characterization, WLAN, Home networks.

Caractérisation dynamique et large bande de la propagation intra-bâtiment à 60 GHz. Architectures des futurs réseaux locaux domestiques sans fil

Résumé

Cet article présente une partie des résultats de la caractérisation de la propagation radioélectrique à 60 GHz en environnement résidentiel, menée par l'IETR. Cette étude s'inscrit dans le cadre du projet RNRT intitulé "COMMINDOR". Ce projet exploratoire s'intéresse aux systèmes de radiocommunications très haut débit (155 Mbit/s) et courte portée (dizaine de mètres) pour les futurs réseaux domestiques, permettant l'interconnexion et le contrôle d'équipements multimédia grand public.

L'étude repose sur des campagnes de mesures effectuées avec un sondeur de canal utilisant la technique du corrélateur glissant, ayant une bande d'analyse de 500 MHz et une résolution temporelle effective de 2.3 ns. Les mesures se sont déroulées dans des environnements résidentiels meublés. L'étude des angles d'arrivée des ondes souligne le rôle des ouvertures (telles que les portes, les escaliers, etc.) dans la propagation entre pièces. Une attention particulière est accordée à l'influence de l'activité humaine sur la propagation. Il en ressort que les déplacements des personnes peuvent rendre le canal indisponible pour des durées de l'ordre de la seconde. A partir de la caractérisation du canal de propagation, plusieurs recommandations concernant le déploiement de réseaux sans fil très haut débit à 60 GHz en milieu résidentiel sont proposées.

Mots Clés : Propagation intra-bâtiment, Ondes millimétriques, Sondage de canal, 60 GHz, Caractérisation spatio-temporelle, WLAN, Réseaux domestiques.

Contents

I. INTRODUCTION

Nowadays, most of high-speed data exchange is performed via wired links: coaxial cables, optic fiber, hybrid fiber coaxial (HFC), etc. One of the actual challenges for radio communications is the design of high-speed (>100 Mbps) wireless local area networks (WLAN). These applications are frequently referred to as Fourth generation (4G) networks [1] or even Fifth generation [2].

The elimination of the physical link (cable) between

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[1]National Telecommunications Research Network

[2]Millimeter waves communications in indoor domestic and residential environment.

devices forming the network makes its deployment easier and improves the device mobility. On the other hand, these advantages go with difficulties due to the waves propagation within a given environment containing several obstacles. Measurements become an essential step in order to characterize the multipath channel and its time-behavior. An accurate description of the spatial and temporal properties of the millimeter-waves channels can be used for the design of broadband wireless 60 GHz high-speed short-range systems and for the choice of the network topology.

High-speed data communications systems use a wide frequency bandwidth. Therefore, due to the congestion of the lower frequencies, it is necessary to explore higher and higher frequency bandwidths. Since several years, millimeter-waves have been proposed for future-generation broadband wireless systems in indoor and short-range outdoor environments [3, 4]. At these frequencies, power loss heavily increases with Transmission-Reception (TR) separation; which allows frequency reuse within any given area, increasing the network capacity. Interference is dramatically reduced; therefore, deployment of this technology by multiple operators in the same area is not problematic. Moreover, the small wavelength permits the design of very compact systems.

In the U.S.A., the 59-64 GHz frequency band is available without a license. In Japan, Ministry of Post and Telecommunications has set the 56-64 GHz band for the developement of various short-range applications. In Europe, the 59.3-62 GHz is proposed for WLAN applications. Recent advances in Monolithic Microwave Integrated Circuit design and processing are promising to make reasonably priced communications systems available. Miniature printed antennas allow cheap packaging of just a few of these MMICs into fully functional transmit/receive modules. Therefore, the knowledge of the basic propagation characteristics at 60 GHz becomes necessary. Several studies were performed in this frequency band, most of them in laboratory rooms, hallways or office building. Most of the time, these rooms were unfurnished or few furnished [5, 6, 7, 8].

Due to the widespread of telecommunications applications, recent years have shown an increasing interest in high-speed home WLANs. In this prospect, the RNRT project "COMMINDOR" [9] concerns the study of high-rate (>155 Mbps) radio communications systems at 60 GHz for future home networks permitting the interconnection and the control of multimedia devices. COMMINDOR is the first national project that allows a detailed characterization of the 60 GHz radio propagation channel.

Within this project, the IETR is put in charge of studying this channel characterization in residential environments. These environments present some particularities: short-range TR separation, rarely exceeding 10 m, various furniture, different wall structures and a particular human activity. Moreover, these residential networks must be thought taking into account ergonomic and cost constraints, as well as installation simplicity.

The aim of this paper is to present some outstanding aspects of the IETR study of the 60 GHz radio propagation in residential environments realized for the COMMINDOR project. This study, based on several measurement campaigns, focuses on characterization of angle-of-arrival (AOA) and human activity influence on 60 GHz radio propagation. Using these results, several recommendations concerning the 60 GHz high-rate WLANs deployed in residential environments are identified.

The paper has three parts. Part II describes some possible network configurations for domestic applications. Part III presents the channel sounder and the measurement campaigns. Site description and measurement scenarios are also described. Finally, part IV presents the measurement results and their impact on the emergent network topologies.

II. HIGH SPEED HOME NETWORKS

A home network represents the inter-connection of several domestic devices as computer devices (PC, printer, scanner, web cam, etc.) or multimedia devices (DVD/CD players, Hi-Fi, loudspeakers, TV. . .). Within the network, these devices can exchange control data, audio/video data, etc. So these devices don't have the same data-rate and quality-of-service (QoS) constraints. The network must completely cover the residential area and have several access points to the external access networks such as telephone networks, Internet or broadcasting networks (radio, television, DVB-S, DVB-T, DVB-C. . .).

Several solutions have been developed or are under study. Some of them are wired networks (power-line networks, USB, Ethernet, 802.11, IEEE 1394). Others are wireless local area networks (WLAN). If wired networks can offer easier high data rates, especially with the 1394 bus, wireless networks offer mobility. Figure 1 shows a distribution of different kinds of networks in terms of mobility and data rates.

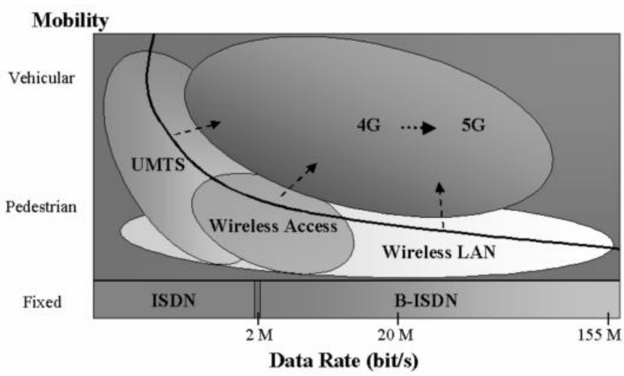


Figure 1: Kinds of networks in terms of mobility and data rates.
Les types de réseaux en fonction du débit et de la mobilité.

WLANs have widespread data rates and different frequency bandwidths, as shown in Table 1.

Frequency	Data Rate	Examples
2.4 GHz	255 k - 10 Mbps	Bluetooth, Home RF, IEEE 802.11b
5.2 GHz	20 Mbps	Hiperlan 2, IEEE 802.11a
17 GHz	10-20 Mbps	Hiperaccess
60 GHz	>100 Mbps	"Wireless IEEE 1394", Wireless ATM...

Table 1: Characteristics of several WLANs.
Caractéristiques de quelques réseaux locaux sans fil.

The actual challenge is to realize a high-speed WLAN with data rates greater that 100 Mbps, i.e. an alternative to the 1394 bus ("Wireless 1394"). Recent researches on 60 GHz systems are conducted in this perspective.

From the user's perspective, a home network must presents some basic features as low cost, maintenance and utilization simplicity. More precisely, the required features are:

- Low cost;
- Low power;
- Reliability;
- Easy installation allowing a fast deployment and user-transparent configuration;
- Facility to add/remove devices to/from the network;
- Facility to accept devices with different complexities;
- Facility to accept different services with different QoS.

One may recognize some of the features of the *ad-hoc* networks where auto-configuration is essential. Several network topologies may be identified according to the way the wired and the wireless techniques are combined. If necessary, the global network (covering all the house) could be divided into several sub-networks. In order of complexity, three conceivable configurations are described.

1 - Wireless extension

The devices are wireless connected to a wired-LAN backbone. Access points (AP) can be used to form a bridge between the LAN and an external access network. All communications between devices or between a device and the access network go through the wired bus (Figure 2).

One can imagine that such a wired LAN could be systematically installed within new houses, with local access nodes placed in the main rooms. Thus, each device could communicate with another, whatever the device locations. In such a case, the network is centralized and global. However, the wired links allow very high data rates (IEEE 1394: from 200 up to 800 Mbps) but have severe limitations concerning the bus length.

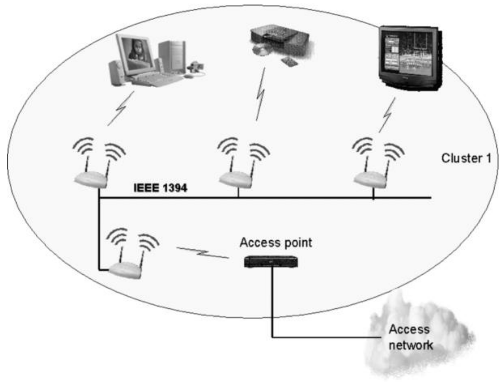


Figure 2: Wireless extension.
Extension sans fil.

2 - Wireless bridge

If the first case is not possible, due to the bus length, the global LAN can be divided into several wired sub-networks (as cluster 1 in Figure 3) or sub-networks of the previous type (wireless extension). The inter-cluster connection is a wireless one. The main difficulty is the data transfer between two unsynchronized clusters (Figure 3).

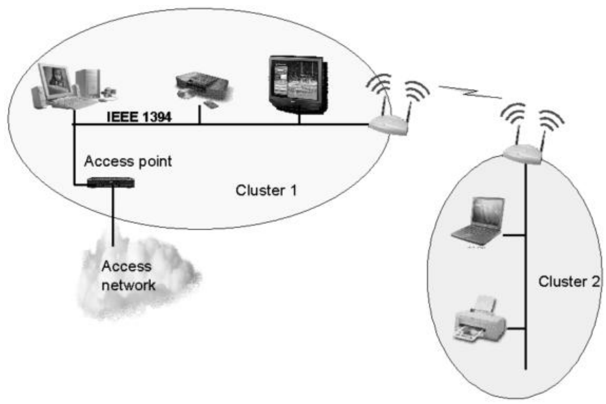


Figure 3: Wireless bridge.
Pont sans fil.

3 - Wireless network

A complete wireless network can also be considered (Figure 4). The global network can be divided into sub-networks (clusters). Each sub-network can be centralized or distributed. The global network is distributed (each sub-network can directly communicate with another one).

In a centralized network, all communications between devices go through an unique point, called "Base Station" (BS). In order to be included in a WLAN, a new device must be able to communicate with the BS. The BS location is therefore an important factor for the network deployment. Two location types can be considered: on the ceiling, in the center of the room (Figure 5-a) or in a corner of the room, next to the ceiling (Figure 5-b).

In the first case, the radiation pattern of the BS antenna must be large, in order to guarantee the radio coverage. In the second case, a sector antenna, with half power

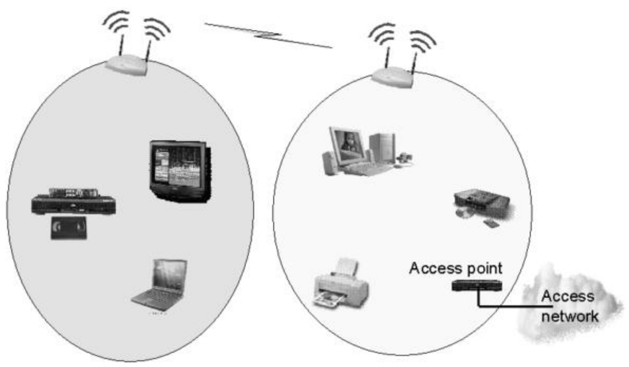
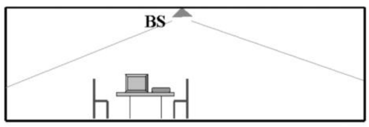
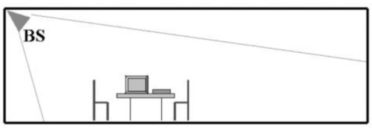


Figure 4: Wireless network.
Réseau sans fil.



(a) Base Station on ceiling



(b) Base Station in a corner

Figure 5: Base Station locations.
Emplacements de la station de base.

beamwidths (HPBW) less than 90° in azimuth and elevation can be used. Usually, a sector antenna has a greater gain than an omni-directional one; therefore, a better link-budget can be obtained. The first case optimizes the distance between a device and the BS. The second one is easier to install and more discreet.

In the case of a distributed (*ad-hoc*) network, devices directly communicate with each other. In order to be included in the network, a new device must be able to identify the other devices forming the network and to communicate with them.

The COMMINDOR project tries to evaluate the feasibility of this last configuration: the complete wireless network. The chosen viewpoint is rather the one of a centralized network, with a BS located in a corner of a room. The measurement campaigns described in the following section have been mainly thought in this way. A central question this study has to answer is about the possibility that a wireless sub-network covers several rooms.

III. CHARACTERIZATION OF THE 60 GHz RADIO PROPAGATION

III.1. Measurement equipment

A channel sounder, based on the sliding correlation technique, has been developed by the IETR [11]. The channel impulse response is evaluated with a temporal resolution of 2.3 ns. The delay observation window can be adjusted from 0 to 1 μs. This window is fixed to 200 ns for the measurement campaigns. As the sliding factor is also adjustable, the measurement duration of the impulse response can be adapted to the channel temporal variations. Therefore, this sounder can observe Doppler shifts up to several kHz. The relative dynamic is 40 dB.

Four antennas are used: two horns and two patches. Horns have a 22.4 dB gain and a 12° HPBW. Patches, as for them, have a 58° HPBW. The patch number one has a 4.3 dB gain. The gain of the second one is 2.2 dB. The vertical polarization is used. The reception antenna is mounted on a motorized system allowing a fine positioning in the horizontal plane. This system also controls the azimuthal rotation of the reception antenna. Thanks to this positioning system, study of small scale phenomena (the wavelength λ is 5 mm) and determination of angles of arrival are made possible. The sounder and the positioning system are driven by a computer that also samples and saves in real time on hard drive the measured impulse responses.

III.2. Measurement environments

Several measurement campaigns have been conducted in several environments. The first campaigns have taken place in the laboratory premises. This environment is characterized by its large rooms (about 100 m^2), the presence of concrete pillars, metallic cupboards, few windows. These campaigns were about line of sight (LOS) measurements with the purpose of determining power loss laws versus the distance.

The next campaigns have been conducted within two houses. One of these houses can be considered as a typical European residential environment. The other one is atypical (it is a leisure center for kids). The building materials are mainly breeze blocks, plasterboards and bricks. There are large double-glazing windows and a fireplace in both houses. During these campaigns, the attention has been particularly turned on the AOA estimation and the influence of several factors (as antennas beamwidth, furniture, movements of people). Afterwards, the typical residential environment is called "House" and the other one is referred to as "C.L.E." (see Figure 6).

The dimensions of the C.L.E. first floor are 13$\times$8$\times$2.9 m. Ones of the House are 10.5$\times$9.5$\times$2.5 m. In both environments, measurements have been mainly realized at the first floor (in 4 rooms in the C.L.E. and in 3 rooms in the House). Measurements between floors have also been realized.

(a) House (b) C.L.E.

Figure 6: Pictures of the measurement environments.
Photos des environnements de mesure.

III.3. Measurement scenarios

III.3.1. Transmission

Most of measurements have been performed from the viewpoint of a centralized network. The transmitting antenna is always the patch 1. It is placed in a corner of the main room of the house, at a height near the ceiling (2.2 m to 2.5 m) and slightly pointed toward the ground. This transmission position is called "TX1" in Figure 7. For the laboratory, the same location type is used.

In order to characterize the propagation between the floors of a house, other TX locations are defined in the entrance hall of the House and the CLE (TX2 and TX3 on Figure 7). One can find stairs leading to the stage in each hall.

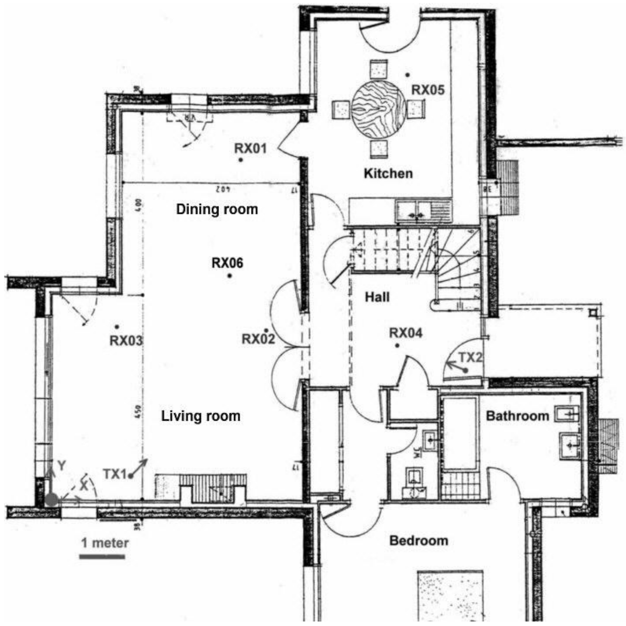
III.3.2. Reception

For each position of the transmitter, several receiver positions are defined. For each position, the two kinds of antennas, horn and patch 2, are successively used. The receiver is placed at a height of 1.20 m, which is about the height of a computer monitor on a desk.

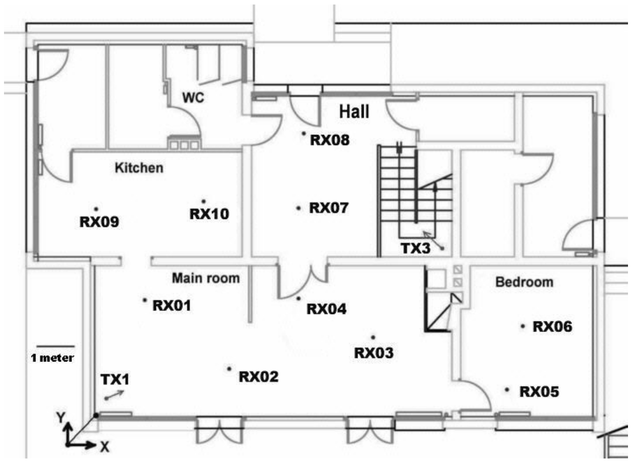
For the laboratory measurements, the receiving antenna is systematically pointed towards the transmitter, in both elevation and azimuthal planes, by means of a manual positioning system. In each receiver position, measurements are done on two perpendicular linear tracks. One of these tracks is oriented toward the transmitter. On each track, about twenty measurements are carried out every $\lambda/4$. For each antenna type, about fifteen positions are defined.

For measurements within residential environments, the receiver antenna has a null elevation angle. An AOA analysis is done: the antenna is rotated over 360° thanks to the motorized positioning system. The rotation step is chosen according to the antenna type: 6° for the horn (60 measurement points) and 12° for the patch (30 measurement points). This rotation is repeated along a 10 λ linear track by a step of λ. A spatial mean calculation along this track can correctly suppress the small scale variations of the channel. A similar method is used in [8].

Then, for a given measurement position, acquisition is done on 300 or 600 measurement points, depending on the



(a) House



(b) C.L.E.

Figure 7: Measurement environments.
Environnements de mesure.

receiver antenna type. During this operation, there is no movement in the channel.

In the C.L.E. and the House, several receiver positions are also chosen upstairs. In these cases, the motorized positioning system could not be used, because of its bulk. As for the laboratory measurement campaigns, the manual positioning system is used instead.

Table 2 lists all measurement positions and indicates the visibility situation for each of them. A plan of the each residential environment is presented in Figure 7. The transmitter (TX) and receiver (RX) locations are indicated on these plans. In the House, the cause of the NLOS situation for RX3 is a furniture element placed between the two antennas. The positions that are listed in Table 2 and that not appear on the plans are located upstairs.

These measurement campaigns have made it possible to constitute a database containing almost 30 000 impulse responses.

Site	Transmission	Reception	
		LOS	NLOS
House	TX1	RX1,2	RX3,4,5
	TX2		RX1,3,5,8,9
C.L.E.	TX1	RX1,2,3,5	RX6 to RX10
	TX3	RX7,8	RX3,4,11,12,13

Table 2: Antennas positions in the House and the C.L.E. (NLOS: Non Line of Sight)
Positions de mesure dans la Maison et le CLE.

III.3.3. Human activity

The temporal evolution of the propagation channel, caused by the movements of people, has also been studied. Measurements have been conducted in the residential environments. During these measurements, antennas are fixed while few persons are moving within the environment. Short-term and long-term analyses are defined.

For short-term analyses, impulse responses are stored during 5 to 40 seconds, while a person walks along a predefined path. The temporal sampling step is 2 ms.

Long-term measurements have only taken place in the House, in the presence of four persons, living normally in the house. Their movements were not "programmed". Thus, the human activity was "natural". These recordings have a duration from 5 to 40 minutes. The temporal sampling step is 1.2 ms. For all these measurements, the sounder observation window is reduced to 120 ns.

IV. RESULTS ANALYSIS

From the database of impulse responses, several propagation characteristics are computed: attenuation, delay spread, delay window, coherence bandwidth [12]. These characteristics are then analyzed in order to determine the influence of the different measurement parameters (antennas beamwidth and polarization, presence of furniture, visibility conditions, movements in the channel, etc.) on the propagation. The noise threshold used for the broadband characteristics computation is adapted for each impulse response. This threshold is limited either by the channel sounder relative dynamic (40 dB), or by the sounder noise level (-120 dBm).

Within the framework of this article, we will focus on two "critical" aspects of the propagation at 60 GHz: propagation under NLOS conditions and human activity. However, to understand the difficulties of the propagation under NLOS conditions, we will begin to analyze the propagation with visibility.

IV.1. LOS Propagation

In a LOS situation, if the receiver antenna is pointed towards the base station in both elevation and azimuthal planes, the measured attenuation, A_{meas}[3], is close to the free space attenuation, given by :

$$A_{FS(dB)} = 20log_{10}(\frac{4\pi d}{\lambda}) - G_{Tx} - G_{Rx} \qquad (1)$$

where G_{Tx} and G_{Rx} are respectively the gains of transmitter and receiver antennas, d is the TR distance and λ is the wavelength.

Frequently, the attenuation under LOS conditions is simply modelized by:

$$A_{mod(dB)} = A + 10\alpha log_{10}(d) \qquad (2)$$

Parameters for this model, A and α, are determined by a linear regression using the measured attenuations and distances. These parameters, computed from the laboratory measurements, are listed in Table 3. The room 1 has a rectangular shape (8.9×11 m). The distances between transmitter and receiver lie between 2 and 11 meters. The room 2 has a shape of "L". The distances lie between 2 and 9 meters.

The offset between measurements and free space path loss is around few dB. This offset can be mainly explained by an imperfect (manual) pointing of the antennas.

Room and antenna	α	A(dB)	ρ	mse(dB)
Room 1, Patch	2.5	56.12	0.95	2.0
Room 2, Patch	2.3	58.99	0.86	2.4
Room 1, Horn	2.1	40.26	0.94	1.8
Room 2, Horn	1.9	44.93	0.83	2.2

ρ: correlation, mse: mean square error.

Table 3: Path loss laws parameters for the laboratory measurements.
Paramètres des lois de pertes en distance issues des mesures au laboratoire.

Measurements in residential environments complete these results with an AOA study, which shows that the major part of the energy comes from the direction of the direct path, but also from the first order reflected paths[4] (as can be seen in Figure 8). The power of these paths is lower by at least 10 dB than the power of the direct path. Higher order reflections are much more attenuated.

The importance of the direct path and the first order reflected paths can also be pointed out from the broadband characteristics. The measurements show that for a reception antenna pointed toward the transmitter (in the azimuthal plane), a rotation of the reception antenna of 0.5 to 2 times its HPBW causes a deep degradation of broadband characteristics such as the 75% coherence bandwidth (from more than 200 MHz to less than 50 MHz). This observation holds for the two kinds of antennas, as we can see in

[3]The measured attenuation is the difference between the power (in dB) of the transmitted signal (before the TX antenna) and the power (in dB) of the received signal (after the RX antenna). Power is computed over all the frequency bandwidth, i.e. 500 MHz.

[4]The order of reflection refers to the number of reflections that a path goes through before it reaches the receiver.

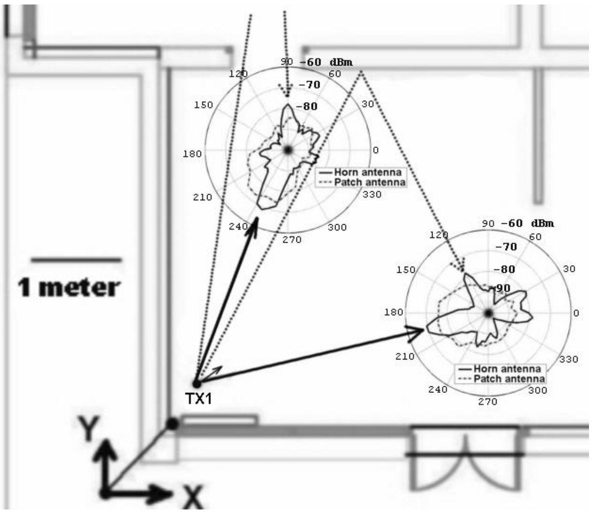


Figure 8: C.L.E. Reveived power in the azimuthal plane (LOS).
C.L.E. Puissance reçue dans le plan azimutal (LOS).

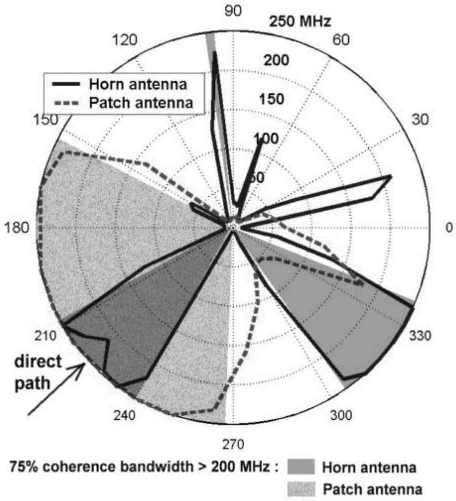
Figure 9-a and 9-b. For the horn, the existence of first order reflected waves assures virtually null frequency selectivity in several AOAs. For the patch, only the direction of the direct path allows very good broadband characteristics, but on a larger angular sector.

The cumulative distribution functions (CDF) are used to evaluate the angular repartition of broadband characteristics. The CDFs are computed from the whole angular measurements for all LOS positions. We determine the percentage of cases for which the studied characteristic exceeds a fixed threshold. Since we have angular measurements, this percentage is directly convertible in degrees. It gives us information on the spread of the angular sector assuring that the chosen value for a characteristic is reached. Table 4 presents these results for the 75% coherence bandwidth and for the 90% delay window. The chosen thresholds are 100 and 200 MHz for the coherence bandwidth, 5 and 10 ns for the delay window. The calculations have been done from the CLE measurements.

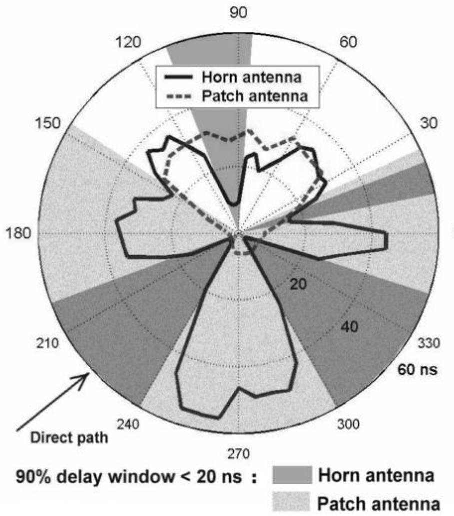
	Horn		Patch	
	%	Sector	%	Sector
$Bc_{75} \geq 200$ MHz	14.2%	51.0°	31.3%	112.5°
$Bc_{75} \geq 100$ MHz	28.3%	102.0°	44.6%	160.5°
$F\tau_{90} \leq 5$ ns	7.9%	28.5°	20.4%	73.5°
$F\tau_{90} \leq 10$ ns	15.2%	54.8°	35.0%	126.0°

Table 4: CLE. Angular coverage and percentils in LOS for broadband characteristics (Bc_{75} : 75% coherence bandwidth, $F\tau_{90}$: 90% delay window).
Couverture angulaire en situation de visibilité dans le CLE pour différentes valeurs de caractéristiques large bande (Bc_{75} : bande de cohérence à 75%, $F\tau_{90}$: fenêtre des retards à 90%).

We note that, for LOS situations, the use of a patch antenna for the receiver has the advantage to assure an important angular coverage, which largely reduce misalignment errors.



(a) House LOS - Bc_{75} - RX02



(b) House LOS - $F\tau_{90}$ - RX02

Figure 9: Horn/Patch comparison of the angular coverage for two broadband characteristics. (Bc_{75} = 75% coherence bandwidth, $F\tau_{90}$ = 90% delay window). NB : calculation of the coherence bandwidth is limited to 250 MHz.
Comparaison Cornet/Patch de la couverture angulaire pour deux caractéristiques large bande (Bc_{75} = bande de cohérence à 75%, $F\tau_{90}$ = fenêtre des retards à 90%). Note : l'évaluation de la bande de cohérence est bornée à 250 MHz.

IV.2. NLOS Propagation

IV.2.1. Propagation between rooms

Whereas the LOS propagation does not pose particular problems, it is not the same under NLOS conditions, and especially when the transmitter and the receiver are in different rooms. At 60 GHz, the penetration loss through the walls is very high. Our measurements show that a 23 cm thickness breeze blocks wall causes about 60 dB penetration loss and a 4 cm thickness door (agglomerated wood) about 15 dB (see also [13]). So the waves propagation at 60 GHz between different rooms shapes difficult.

In NLOS situations, a satisfactory correlation between the distance and the measured attenuation could not be found. It is not conceivable to obtain a law linking these values, in any case not for the distance range covered by our NLOS measurements (5 to 11 m). Then, the additional attenuation with respect to the free space path loss is computed. For this calculation, the minimum attenuation measured over 360° is considered, corresponding to the main direction of arrival. Then A_{ex} (in dB) is computed as: $A_{ex} = A_{meas} - A_{FS}$. The results are given in Table 5.

A_{ex}	Horn		Patch	
(dB)	House	CLE	House	CLE
mean	–	30.2	–	17.5
standard deviation	–	3.8	–	3.2
minimum	10.2	24.5	1.6	12.6
maximum	30.2	35.9	17.4	22.1

Table 5: Additional attenuation in comparison with free space in NLOS for measurements between rooms
NB: no significant mean and standard deviation for House, due to few measurement points.
Atténuation supplémentaire par rapport à l'espace libre en situation de non visibilité. Note : pas de moyenne et d'écart-type pertinents pour la Maison, du fait du peu de points de mesures.

The difference between the two environments is notable. The main explanation is the location of the NLOS positions. In the House, only two NLOS positions are considered (RX4 and RX5). The position RX5 is rather particular because of an important reflected path just passing through the door (see Figure 10). In the CLE, some positions are far from the doors separating the rooms. These cases are particularly difficult.

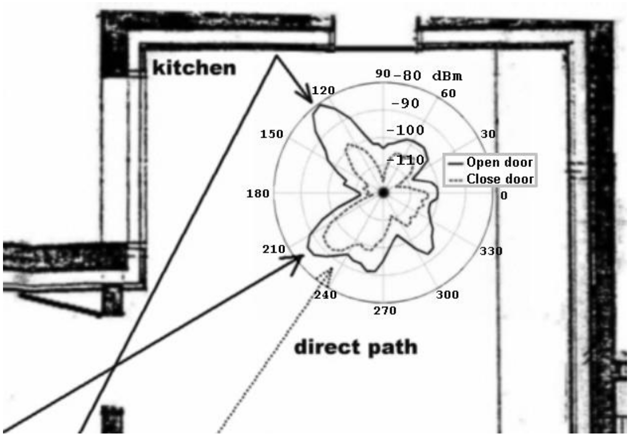


Figure 10: House. Received power in the azimuthal plane, in NLOS with a receiving horn antenna.
Maison. Puissance reçue dans le plan azimutal, en NLOS avec une antenne cornet en réception.

We consider the CLE as a "worse case". Then, with the considered antennas configurations and for a 11 m TR separation, we have to reckon on an average attenuation of 92.3 dB for a horn antenna and of 99.8 dB for a patch antenna.

The attenuation A_{ex} is greater for a RX horn antenna. This observation can also be noted on the difference between the attenuation measured with a patch and the one measured with the horn. This difference is 7.5 dB (standard deviation: 2.7 dB) in the CLE and 8.3 dB (standard deviation: 3.6 dB) in the House. These values are very far from the difference between the gains of the two RX antennas, which is 20.2 dB. This difference shows a not insignificant angular dispersion for NLOS positions. The patch, which beamwidth is larger than the one of the horn, gains by this angular dispersion. One can also note that the elevation angle of the RX antenna was null. In the case of paths arriving with an important elevation angle, the horn antenna is disadvantaged again. The same remark is noted in [16] with similar antenna beamwidths.

The AOA analysis allows a better understanding of the NLOS propagation. By superposition of the polar diagrams of the received power with the site maps, the important role of the openings can clearly be noticed (Figure 10). The directions of arrival for which the received power is greater fit with paths crossing the doors between the TX room and the RX room. This is also unlighted by the comparison of measurements done with open doors and close doors for several positions. The average global difference between the two configurations lies between 8 and 10 dB. For the main direction of arrival, the additional average attenuation when doors are closed is 11.8 dB (standard deviation: 1.8 dB). This value lies within the interval given in [16]: 7 to 15 dB.

In order to have a better understanding of the depicted phenomena, the use of a ray tracing tool is interesting. One of the COMMINDOR partners takes part in the channel characterization with its ray tracing software. Figure 11 shows the power coverage obtained by ray tracing in the House [14]. The TX antenna is the patch 1 and the RX antenna is the horn. During the simulation, for each reception point, the horn is pointed towards the azimuthal direction allowing the highest received power. The role of the doors is underscored again on this map, as well as the presence of main directions of arrival. These directions directly depend on the geometrical configuration of the scene.

The angular dispersion noticed in NLOS situation with patch antennas is interesting for link budgets, but on the other hand it increases the frequency selectivity of the channel. The CDFs for several broadband characteristics are computed as for LOS situations. The results are given in Table 6.

The angular sectors with virtually null frequency selectivity are very sharp. These sectors can be distributed in several directions of arrival. Figure 12 shows the example of RX7 in the CLE. On the polar graph of the coherence bandwidth, there are three angular sectors of about six to ten degrees in three different directions for which Bc_{75} is greater than 200 MHz. The comparison between the two RX antennas shows that a directional antenna can significantly reduce the frequency selectivity. Indeed, according to our measurements, the coherence bandwidth does not exceed 200 MHz with a receiving patch antenna, and is greater than 100 MHz in only 4% of cases.

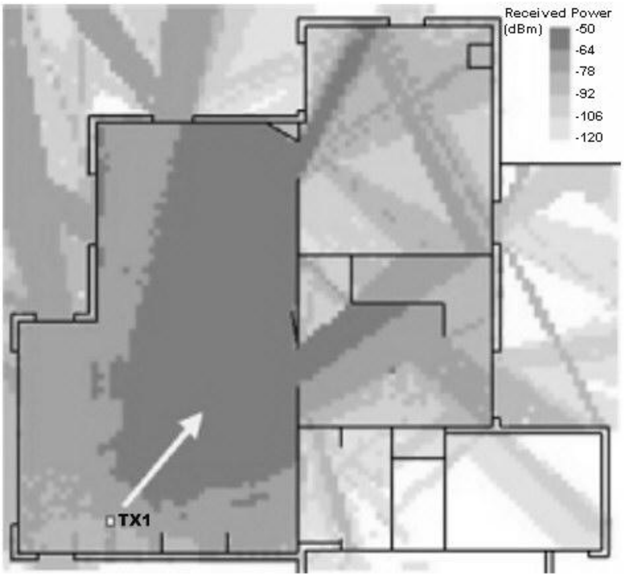


Figure 11: Power coverage map in the House, realized by ray tracing technique (Transmission TX1: patch / Reception: horn).
Carte de couverture en puissance dans la Maison, réalisée par lancer de rayons (cf. [14]). Patch en émission / Cornet en réception.

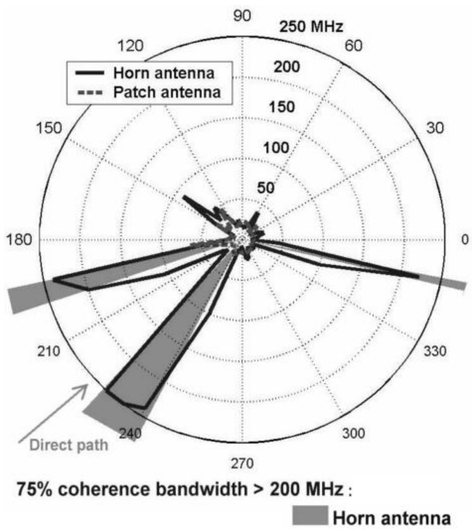
	Horn %	Horn Sector	Patch %	Patch Sector
$Bc_{75} \geq 200$ MHz	2.7%	9.6°	0.0%	0.0°
$Bc_{75} \geq 100$ MHz	8.7%	31.2°	4.0%	14.4°
$F\tau_{90} \leq 5$ ns	0.7%	2.4°	0.0%	0.0°
$F\tau_{90} \leq 10$ ns	2.5%	9.0°	1.3%	4.8°

Table 6: CLE. Angular coverage in NLOS situation for two broadband characteristics (Bc_{75} : 75% coherence bandwidth, $F\tau_{90}$: 90% delay window).
Couverture angulaire en situation de non visibilité dans le CLE pour deux caractéristiques large bande (Bc_{75} : bande de cohérence à 75%, $F\tau_{90}$: fenêtre des retards à 90%).

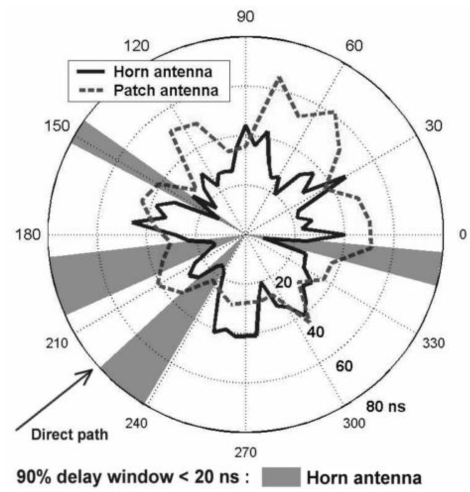
IV.2.2. Propagation between floors

The importance of openings for the propagation between rooms has been underscored. It is the same for the propagation between floors. There is generally a concrete flagstone separating the different floors of a house, which causes very important loss at 60 GHz. The main "opening" between floors is generally a staircase. In the CLE, stairs are in the entrance hall. They are rather "open" (there is a banister with metallic bars). In the House, stairs also lead to a mezzanine overhanging the hall. The opening space between the floors is here very wide, since the ceiling has the height of the house.

For each TX1 location, the power received at the top of the stairs was less than the noise level of the channel sounder (-120 dBm in this configuration). Then, other TX positions have been explored. In the CLE, there are TX2 (at the top of the stairs), TX3 (halfway up on the stairs) and TX4 (in a room upstairs whose door opens onto the stairs). In the House, only one other position is chosen (TX2) placed in the hall at 2.70 m in height. The comparison between the TX2, TX3 and TX4 positions in the CLE has shown that the TX3 position gave the best distribution of the energy between the two levels.



(a) CLE NLOS - Bc_{75} - RX07



(b) CLE NLOS - $F\tau_{90}$ - RX07

Figure 12: Horn/Patch comparison of the angular coverage for two broadband characteristics (Bc_{75} = 75% coherence bandwidth, $F\tau_{90}$ = 90% delay window).
Comparaison Cornet/Patch de la couverture angulaire pour deux caractéristiques large bande (Bc_{75} : bande de cohérence à 75%, $F\tau_{90}$: fenêtre des retards à 90%).

All the receiver positions are in NLOS situations. The additional attenuation with respect to free space loss is computed. The results are presented in Table 7. The difference between the two environments is explained in this case by the hall configuration.

The propagation between floors is still more difficult than between adjacent rooms. The TX antenna is higher in these measurement scenarios (TX2 at 5.10 m, TX3 at 3.60 m, TX4 at 5.15 m for the CLE measurements, and TX2 at 2.70 m for the House measurements) than in the previous ones (TX1 at 2.50 m in the CLE and at

A_{ex} (dB)	Horn House	Horn CLE	Patch House	Patch CLE
mean	23.5	39.0	15.4	–
standard deviation	6.6	5.8	6.1	–
minimum	12.8	30.4	5.1	21.0
maximum	30.4	42.9	20.5	33.0

Table 7: Additional attenuation in comparison with free space in NLOS situation, for measurements between floors.
NB: no significant mean and standard deviation for the receiving patch in the CLE, due to few measurement points.
Atténuation supplémentaire par rapport à l'espace libre en situation de non visibilité, pour des mesures entre étages.
Note : pas de moyenne et d'écart-type pertinents dans le CLE avec un patch en réception, du fait du peu de points de mesures.

2.20 m in the House)[5]. Because of this greater difference between the height of the transmitter and the receiver, the contribution of paths arriving with an important elevation angle is probably greater. This increases the measured attenuation, especially with a receiving horn antenna.

IV.3. Human activity

At 60 GHz, the human body is a significant obstacle for the waves propagation. Few studies based on measurements have been published on this subject within this frequency band [17]. However, human activity is a major problem for the quality of high data rate applications.

Measurements have then been conducted in the CLE and the House in order to characterize the shadowing aspects caused by the human presence.

IV.3.1. Short-term study

In this part, we will focus on one of the measurement scenarios in the House. It is about a series of measurements performed for a NLOS link. The transmitter position is TX1 and the receiver position is RX5 (as shown in Figure 13). The receiver antenna is oriented in the azimuthal plane to maximize the received power. One person moves through the environment, starting in the TX room and stopping in the RX room. The person's route is shown in Figure 13. When moving from one room to the other, at a speed of 1 m/s, the person closes the door. This scenario is repeated for two heights of the transmitting antenna (2.20 m and 1.20 m) and for the two kinds of receiving antenna (patch and horn).

Figure 14 shows the temporal evolution of the measured attenuation for three scenarios. When the transmitting antenna is as high as the receiving one, we can observe a series of attenuation peaks each time the person crosses the main path (shown in Figure 13). On the other hand, when the transmitter is close to the ceiling (2.20 m) the wave is propagated above the person and there are no more attenuation peaks. Around the 17^{th} - 18^{th} second, the person closes the door. From this moment, the attenuation increases by about 15 dB.

[5]Heights above the first floor

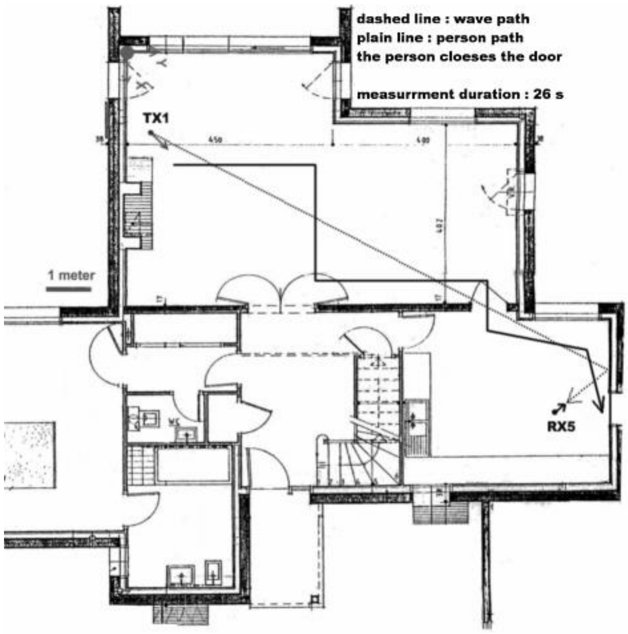


Figure 13: Measurement while a person is walking within the House.
Mesure lors du déplacement d'une personne dans la Maison.

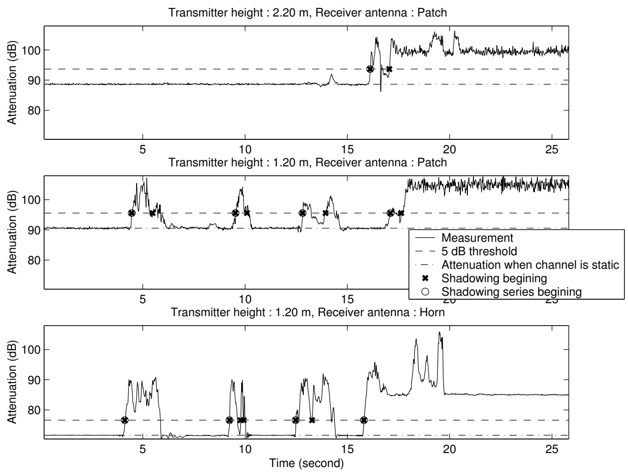


Figure 14: House. TX1/RX5. Temporal evolution of the attenuation while a person walks and closes a door.
Maison. TX1/RX5. Evolution temporelle de l'atténuation lorsqu'une personne se déplace et ferme une porte.

A finer analysis of the attenuation peaks is discribed below. We introduce the notion of "shadowing event" in the following terms. A "shadowing event" is detected as the attenuation becomes greater than a threshold. This threshold is chosen with respect to the measured attenuation when there is no activity in the channel. After optimization, it is set to 5 dB, in order to be sure that it is exceeded only when a person interacts with waves. Using this threshold, it is possible to define the beginning (positive crossing of the threshold, instant $T\ beg$) and the end (negative crossing of the threshold, instant T_{end}) of the "shadowing event", and then to evaluate its duration D:

$$D = T_{end} - T_{beg} \qquad (3)$$

Its amplitude A is calculated as follows:

$$A = Att_{shadow} - Att_{nomvt} \quad (4)$$

where Att_{nomvt} is the attenuation measured without movement and Att_{shadow} is obtained by :

$$Att_{shadow} = \frac{2}{D} \int_{T_{beg}+\frac{D}{4}}^{T_{end}-\frac{D}{4}} Att(t)\mathrm{d}t \quad (5)$$

where $Att(t)$ is the temporal evolution of the measured attenuation. As the attenuation is not constant during the "shadowing event", Att_{shadow} is evaluated by an average over a time window centered on the middle of the "shadowing event". The width of this window is set to $\frac{D}{2}$ to eliminate the contribution of the "sides" of the attenuation peak.

This analysis is carried out on the part of the acquisition before the door is closed. When the transmitter is 2.20 m height, there is no "shadowing event" as can be seen in Figure 14. When the transmitter is 1.20 m height, three series (or "bursts") of "shadowing events" are detected for each kind of receiving antenna. Each series can be made up of several close "shadowing events". Each series is caused by the crossing of the main waves path with the route of the person. The begining of each series is marked with a circle in Figure 14 and the begining of each "shadowing event" is marked with a cross. The characteristics of these series of "shadowing events" are presented in Table 8. The amplitude of a "shadowing events" series is defined as the maximum amplitude of the "shadowing events" forming the series. The duration of a series is the time between the begining of the first "shadowing event" of the series and the end of the last one. One can notice that the phenomenon is stronger in duration and amplitude when the horn is used.

	Antenna	Series 1	Series 2	Series 3
Duration	Horn	1.739 s	0.780 s	1.899 s
	Patch	1.399 s	0.640 s	1.539 s
Amplitude	Horn	13.1 dB	16.7 dB	16.4 dB
	Patch	11.3 dB	11.8 dB	9.1 dB

Table 8: House. TX1/RX5. Characteristics of the series of "shadowing events".
Maison. TX1/RX5. Caractéristiques des séries de "masquages".

About the amplitude, it can be mainly explain by the difference between the antennas gains. When the patch is used, the received power is low. When a "shadowing event" occurs, the received power level corresponds to the noise level. The amplitude evaluation of the "shadowing event" is then limited by the measurement dynamic. When the horn is used, the received signal level is higher and this limitation does not occur; therefore the measured amplitude is greater. A second explanation can complete the first one. Seen from the receiving antenna, the moving person shadows a given angular sector. Referred to the antenna beamwidth, this sector is larger for the horn case. With the patch, it is possible that secondary paths arrive in the main lobe of the antenna, even if a person shadows the main path. This can explain both the smaller amplitude of the "shadowing event" and the shorter crossing duration of the 5 dB threshold.

As shown in Figure 15, the time evolution of the 75% coherence bandwidth is strongly correlated with the one of the attenuation. When the "shadowing event" occurs, the coherence bandwidth decreases by several hundreds of MHz. This is more due to the low signal to noise ratio observed during the shadowing event, rather than to an increase of the delay spread. We can note that in the case of the horn, due to its gain, the received power level after the door is closed is high enough to keep the same broadband characteristics.

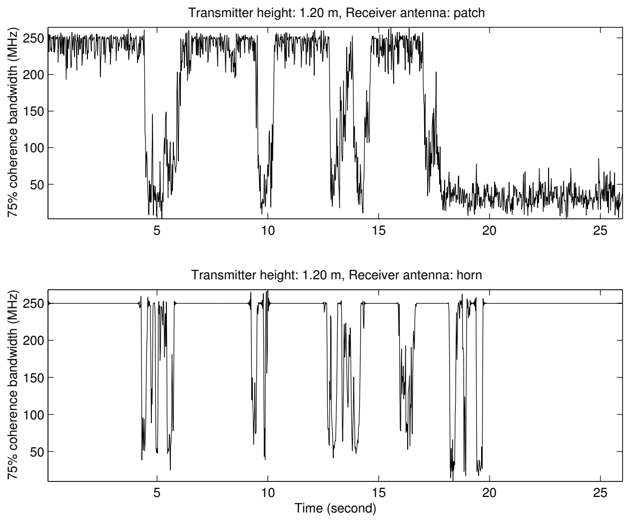


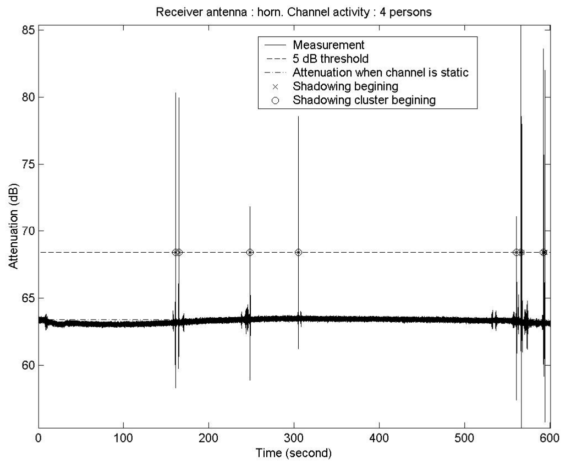
Figure 15: House. TX1/RX5. Temporal evolution of the 75% coherence bandwidth.
Maison. TX1/RX5. Evolution temporelle de la bande de cohérence à 75%.

From these results, the state of the propagation channel is quasi binary: the radio link can be considered as either available, either not. The same comment is done in [18] for 40 GHz radio links. Our measurements reveal unavailability durations of the order of the second, which is very important compared to the data packets duration in a high-speed network. In addition, synchonization problems have to be taking into account.

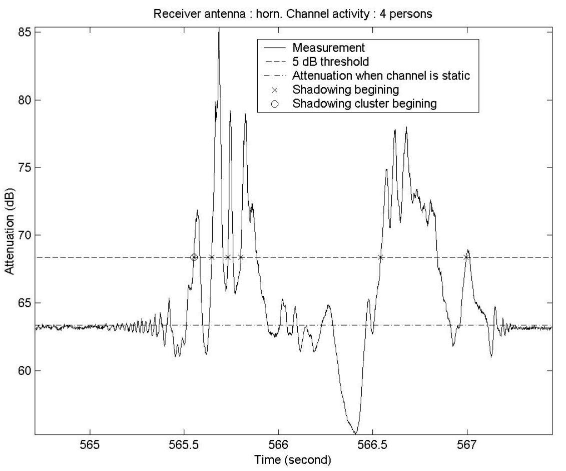
IV.3.2. Long-term study

In order to have a better knowledge of the channel unavailability rate, longer acquisitions have been carried out in the House in the presence of four persons. The transmitter is placed in TX1 position. The receiver is in RX6, on the dinning-room table, at 5 m of the transmitter, in LOS situation (see Figure 7-a. The four persons are in the living-room, that is to say between the two antennas. Their movements are then likely to shadow the direct path. Their activity is "natural" (not controlled for the measurement needs) and can be described as "poor". Most of the time the four persons were seated. Generally, only one person walks in the same time (for example going out of the room and coming back latter). The measurement duration is 10 minutes with the horn and 40 minutes with the patch.

Figure 16 presents the time evolution of the attenuation for the receiving horn antenna. Short peaks can be seen when people walk between the antennas. These peaks often go with "attenuation hollows", that is to say the attenuation decreases. This decrease generally happens just before and just after the peak, and goes with fast and shallow fluctuations. This is the mark of an intervention of the human body as a reflector. Just before the wave path is shadowed, a reflected path is created on the body, very close to the direct one (the path difference is less than the system resolution). This reflected path can constructively interact with the direct path and then the attenuation decreases.



(a) Total acquisition: 10 minutes



(b) Extract: about 2.5 s

Figure 16: House. TX1/RX6. Reception: horn. Temporal evolution of the attenuation with 4 persons living in the House.
Maison. TX1/RX6. Réception : Cornet. Evolution temporelle de l'atténuation en présence de 4 personnes.

Table 9 shows the characteristics of the series of "shadowing events". There is no significant difference between the two kinds of antennas. The line labeled "Unavailability rate" presents the ratio of the sum of the "shadowing events" durations on the measurement duration. This is just an indicative value, since it strongly depends on the people activity. A larger set of measurements is necessary to give a statistically relevant value.

The maximum "shadowing event" amplitude is about

Antenna :	Horn	Patch
Number of "shadowings"	8	8
Mean duration	0.688 s	0.278 s
Max. duration	2.052 s	0.506 s
Mean amplitude	10.0 dB	12.2 dB
Max. amplitude	16.8 dB	14.7 dB
Unavailability rate	0.8%	0.1%
Measurement duration	10 min	40 min

Table 9: TX1/RX6. 4 persons in the House. Characteristics of the "shadowing events" series.
TX1/RX6. Caractéristiques des séries de masquages pour des mesures en présence de 4 personnes dans la Maison.

15 dB, but this maximum is itself an average amplitude over the duration of the "shadowing event". The maximum amplitude during a "shadowing event" can rise up to 20 dB.

IV.4. Discussion

The previous results show that two particularities of the propagation at 60 GHz turn out to be problematic for the performances of very high data rate networks: the shadowing phenomenon and the difficult conditions of inter-rooms propagation.

It seems advisable to consider that the channel is unavailable during the major part of the duration of a "shadowing events" series. The data transfer is then interrupted. If there is no real-time constraint, a simple solution is to transmit the data again, once the channel becomes available. However, if a real-time constraint exists, this solution is not possible.

On the NLOS propagation, it has been noted that the use of a directional receiving antenna is interesting for its gain and the reduction on the frequency selectivity. Nevertheless, these advantages are reached providing that an appropriate pointing is assured. There is nothing intuitive about this pointing, because it depends on the premises layout and on the antennas locations.

Therefore, it is necessary to provide suited solutions to assure the feasibility of such wireless networks. We will mention some of them, in order of complexity.

IV.4.1. LOS Links

In order to simplify the network complexity, one can decide to content oneself with LOS links. The choice of a centralized network, with a BS preferably located on the ceiling center of the room, is a good option. The height of the base station can partly reduce the shadowing aspects. The different devices forming the network could be equipped with more or less directional antennas, pointed toward the base station. If these antennas are not very directional, a manual pointing (which is the user's responsibility) can be considered. If the directivity is greater, an automatic pointing using smart antennas is needed. In this configuration, only the contribution of the direct path is sought, and classical (mono carrier) modulations could be used. This kind of layout has been notably proposed in [19] for office environments.

The global home network will be divided in sub-networks. A sub-network will cover only one room.

IV.4.2. Angular diversity

The measurements have underscored the angular diversity in both LOS and NLOS situations. It seems to be usefull to take advantage of this diversity. Thus, if a wave path is shadowed by a person, a path can arrive from another direction and thus can keep the link (Figure 17).

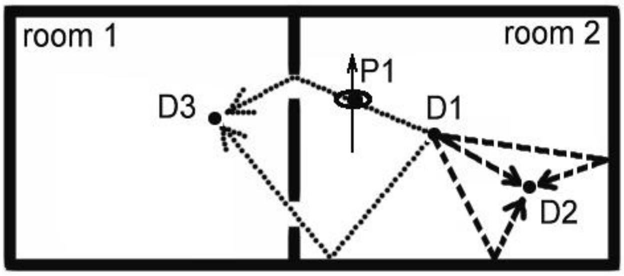


Figure 17: Example of a network with angular diversity for LOS and NLOS links. D#: device #, P: person. One of the devices can be a BS in a centralized network.
Exemple de réseau avec diversité angulaire pour des liaisons LOS et NLOS. D# : équipement n°#, P : personne. Un des équipements peut être une SB dans un réseau centralisé.

This implies the implementation of more complex systems. Two approaches can be distinguished. The first one consists in the use of several more or less directional antennas. These antennas are arranged in a circle in order to cover the 360° of the azimuthal plane. It could also be advantageous to add coverage in elevation. Then the receiver proceeds to a selection of the antenna allowing the best link budget. This solution has the advantage of presenting a gain in all directions. It also allows to reduce the channel frequency selectivity and therefore to simplify the processing. Classical mono-carriers modulations could be sufficient in this case.

The second approach would try to process the paths diversity with appropriate receivers equipped by omni- directional antennas (RAKE, OFDM…). This approach lays the emphasis on the "system" aspect rather than on the "antenna" aspect.

These solutions would make possible to consider radio links between adjacent rooms and to correctly counter the "shadowing" effects. The coverage of a whole floor of a house is then possible. In this configuration, it is important that a great density of paths exists to assure the angular diversity.

The network can be centralized or distributed. If it is centralized, the location of the base station should be optimized depending on the desired coverage. To extent the network coverage to the whole house, it will probably be necessary to divide the network into sub-networks, particularly for transmission between devices located on different floors. There would typically be a minimum of one sub-network per floor. The use of a judiciously placed relay could manage the transit between two base stations (in the case of centralized sub-networks) or between two devices belonging to two sub-networks (in the case of a distributed network).

IV.4.3. Site diversity

In the continuation of the previous solution, the diversity of possible paths to link two devices can be reinforced. This could be done by giving the ability for a device of the network to use another one as a relay point. The multi-rooms links would still be facilitated, and shadowing problems still reduced. In the example of Figure 18, device D1 can establish a radio link with device D3 located in an adjacent room, with the help of the device D2 as a relay. The links D1-D2 and D2-D3 are LOS links. Moreover, if the relected path passing through the other door is broken, the data transfer can go on thanks to these links.

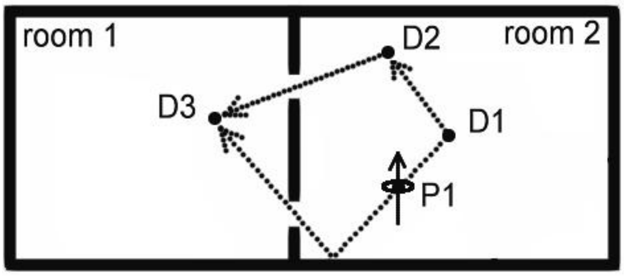


Figure 18: Example of a network with site diversity for LOS and NLOS links. D#: device #, P: person.
Exemple de réseau avec diversité de site pour des liaisons LOS et NLOS. D# : équipement n°#, P : personne.

These additional advantages are directly dependent on the number of devices in the network. The more numerous the devices would be, the more important the possibilities of relaying the communications.

Moreover, this configuration can potentially reduce the transmitted power, as the propagation distance would be shortened. It can also make the links between floors possible, according to the devices locations, and providing that the elevation angles are processed. The counterpart naturally lies in the increase of complexity that perhaps goes beyond low cost and general public applications. Each device should initiate a link while being able to be used to relay another communication within the network.

Such a solution is rather understandable in a distributed network perspective.

V. CONCLUSION

This paper has presented some results of the study conducted by the I.E.T.R. on the 60 GHz radio propagation in residential environment, in the context of a R.N.R.T. project called "COMMINDOR". This study is an essential step in the definition of high data rate (155 Mbps) and short range (about ten meters) radiocommunications systems for future home networks. The study is based on measurement campaigns. Attention has been particularly paid to NLOS links. The angles of arrival study shows the strong contribution of openings between adjacent rooms. Measurements on the human presence have revealed that attenuation peaks occurred when somebody shadows a significant path. These peaks can have amplitudes up to about 16 dB, and durations of about one second.

From these results, some solutions are proposed in order to assure the feasibility of multi-rooms links, free from shadowing effects caused by human activity. These solutions suggest taking advantage of the channel angular diversity, thanks to adequate antennas processing. These techniques can be complex but are necessary for future ad-hoc wireless home networks with high performances.

Acknowledgment

The authors would like to thank all the COMMINDOR project's partners.

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